AD NUMBER

AD893602

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; FEB 1972. Other requests shall be referred to Air Force Rocket Propulsion Lab., Edwards AFB, CA 93523.

AUTHORITY

AFRPL ltr, 31 Jan 1974

AFRPL-TR-72-39

TWR-5605

SPECIAL REPORT

GRAIN STRESS ANALYSIS STUDY - PHASES II AND III

(OOAMA/RPL STRESS MOTOR SN 0012257)

FEBRUARY 1972

Thiokol / WASATCH DIVISION
A DIVISION OF THIOKOL CHEMICAL CORPORATION

AFRPL-TR-72-39

TWR-5605

SPECIAL REPORT
GRAIN STRESS ANALYSIS STUDY - PHASES II AND III
(OOAMA/RPL STRESS MOTOR SN 0012257)

Contract F04611-72-C-0015

February 1972

Prepared by

THIOKOL/WASATCH DIVISION
A Division of Thiokol Chemical Corporation
P.O. Box 524, Brigham City, Utah 84302 801/863-3511

for T J Golding
U. E. Garrison, Manager
Minuteman Programs

Prepared for

AIR FORCE ROCKET PROPULSION LABORATORY
AIR FORCE SYSTEMS COMMAND
Edwards AFB, California

Distribution limited to U.S. Gov't agencies only: (Information covering test and evaluation of military hardware); (February 1972). Other requests for this document must be referred to AFRPL (STINFO/DOZ), Edwards, CA 93523.

Publications No. 0272-36008

FOREWORD

This Special Report represents the work performed by Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah, under Contract F04611-72-C-0015 from 1 Nov 1971 thru 29 Feb 1972.

Technical direction was provided by the Air Force Rocket Propulsion Laboratory at Edwards Air Force Base, Edwards, California.

This technical report has been reviewed and is approved.

R. G. Schuder, Capt/USAF
Project Engineer/AFRPL

ABSTRACT

This report presents a theoretical stress analysis of OOAMA/RPL motor S/N 0012257. The analysis involved motor tip-over from horizontal to vertical position and rerun of the board course reported previously in Thiokol document TWR-4728. The results reported represent a major step in the use of instrumented motors to verify the accuracy of modulus dependent predictions of rocket motor grain structural behavior.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF SYMBOLS

σ_r	Radial stress at the case/propellant bondline
σ_{rh}	σ_r due to a horizontal slump load
σ_{rv}	σ_r due to a vertical slump load
σ_{rax}	σ_r due to a uniform thermal load applied to an axisymmetric geometry
σ_{rs}	σ_r due to a uniform thermal load applied to a plane strain star geometry
σ_{rc}	σ_r due to a uniform thermal load applied to a plane strain cylindrical geometry
σ_{rt}	σ_r due to a thermal gradient load applied to a plane strain cylindrical geometry
ϵ_θ	Hoop strain at the star tip
$\epsilon_{\theta h}$	ϵ_θ due to a horizontal slump load
$\epsilon_{\theta v}$	ϵ_θ due to a vertical slump load
$\epsilon_{\theta va}$	Bore hoop strain due to a vertical slump load applied to an axisymmetric geometry
$\epsilon_{\theta s}$	ϵ_θ due to a uniform thermal load applied to a plane strain star geometry
$\epsilon_{\theta c}$	Bore hoop strain due to a uniform thermal load applied to plane strain cylinder geometry
$\epsilon_{\theta ax}$	Bore hoop strain due to a uniform thermal load applied to an axisymmetric geometry
$\epsilon_{\theta t}$	Bore hoop strain due to a thermal gradient load applied to a plane strain cylinder geometry
τ	Shear stress at the case/propellant bondline
τ_v	τ due to vertical slump loads

I. INTRODUCTION AND SUMMARY

This report presents the results of a theoretical stress analysis of the OOAMA/RPL stress motor, S/N 0012257. The data presented form a continuation of the analysis described in ref 1.

The test conditions considered in this analysis were:

1. Tip-over from horizontal to vertical position and back to the original horizontal position. The motor remained in the vertical position for approximately 3 days.

2. Rerun of the board course test as described in ref 1.

The tip-over analysis includes the effects of the change from horizontal to vertical slump loading. In addition, whenever possible, an attempt was made to compensate for thermal gradients that occurred within the motor during the tip-over test.

The predicted variations in the stresses and strains experienced by the motor during the tip-over from horizontal to vertical are dependent on grain location. The maximum predicted variations were as follows:

1.	Normal stress at the case (psi)	2.59
2.	Shear stress at the case (psi)	0.87
3.	Bore strain (%)	2.71

In addition, the following variations were predicted due to thermal gradient changes:

1.	Normal stress (psi)	-0.4
2.	Bore strain (%)	-1.23

No attempt was made to predict thermal gradient effects on shear stress. Table I shows the results of the tip-over analysis for various times during the test for the applicable gages.

The dynamic analysis was based on the same analysis techniques used in the previous analysis (ref 1). Various loading conditions were obtained by traversing a spaced board course with a GFE transporter pulled by a tractor. Vertical accelerations (single amplitude) measured in the propellant grain varied from 0.31 to 1.11 g's. Resultant predicted values of stress and strain are shown in Table II. Additional accelerometers mounted on the starpoints indicated that the entire grain responds to the same transportation frequency. No measurable phase lag was observed in any of the accelerometers.

II. ANALYSIS METHOD

Budget and time considerations dictated that large computer runs be kept to a minimum. Previously generated grids and runs were used wherever possible. However, an axisymmetric equivalent port area grid (Figure 1) was required. Three parameters are of interest in this analysis.

1. Normal stress at the bondline (σ_r), gages N1, N2, and N3 located at planes 70, 31, and 70, respectively.
2. Shear stress (τ), gages SC1, SC2, S1, S2, and S3 located at planes 70, 31, 200, 60, and 200, respectively.
3. Bore strain at the star tip (ϵ_θ), gages C1 thru C8, located at planes 31 and 70.

Gage locations are shown in Figures 2 and 3.

Computer programs utilized in the analysis were:

1. S3016, A Finite Element Plane Strain Stress Analysis Program, ref 2.

2. S3036, An Axisymmetric Finite Element Stress Analysis Program, ref 3.

3. S3053, Elastic Hollow Cylinder Stress Analysis Program.

4. S3069, Linear Viscoelastic Hollow Cylinder Program, based on theory presented in ref 4.

A. TIP-OVER TEST ANALYSIS

1. Horizontal Slump Load

The analysis assumes that all stresses and strains are zero when the motor is in the horizontal position (gages calibrated to read zero). Actually the bulk of the grain is responding to a 1 g horizontal slump load. When the motor is positioned vertically, the 1 g horizontal slump load will relax or subtract from the zero gage readings. This effect must be taken into account in analysis of the vertical slump load.

This analysis was made with the use of Program S3016. A 1 g slump load was applied to the propellant grain with a body force applied uniformly around the case to obtain an equilibrium force balance. A 180 deg symmetrical sector of a cross-sectional slice through the motor was utilized. The resulting input grid is shown in Figure 4. Parameters obtained from this analysis were σ_{rh}, $\epsilon_{\theta h}$, and τ predicted for each applicable gage location.

2. Vertical Slump Load

This analysis consisted of a run on Program S3036 utilizing an axisymmetric grid with an equivalent port area smooth bore geometry (Figure 1). Loading consisted of a 1 g vertical slump reacted at the aft skirt and a 1,500 lb load

applied at the forward skirt to incorporate the effects of the forward lifting ring. Parameters obtained from this run were σ_{rv}, ϵ_{va}, and τ_v for each applicable instrumentation plane. Two additional runs were made with a thermal load applied. These were a plane strain run with Program S3016, with the geometry and grid shown in Figure 5 and a plane strain equivalent port area cylinder. Parameters obtained from these runs are $\epsilon_{\theta s}$ and $\epsilon_{\theta c}$ respectively.

These data were then used to obtain a concentration factor (K) for subsequent adjustments of the axisymmetric output to the star geometry. These adjustments were made for each plane of interest as follows:

$$\epsilon_{\theta v} = K\,\epsilon_{\theta va} \qquad \text{where} \quad K = \epsilon_{\theta s}/\epsilon_{\theta c}$$

3. Thermal Gradient Analysis

The motor experienced significant thermal gradient changes during the tip-over test. Outside temperatures dropped to a low level during the test causing the case and propellant near the case to drop to a temperature considerably lower than the storage temperature.

Normal stress and bore strain data were adjusted to reflect these temperature changes at several times during the test cycle.

The following runs were required to make the above described adjustments.

1. Axisymmetric equivalent port area (Figure 1) with uniform thermal load. The output parameters were σ_{rax} and $\epsilon_{\theta ax}$.

2. Plane strain star geometry (Figure 6) with uniform thermal load. The output parameters were σ_{rs} and $\epsilon_{\theta s}$.

3. Plane strain equivalent port area cylinder with uniform thermal load identical to a and b. The output parameters were σ_{rc} and $\epsilon_{\theta c}$.

4. Plane strain cylinder geometry with equivalent port area. These runs used temperature gradient data for each time considered and were obtained from thermocouples T9 thru T13 (Figure 3). The output parameters were σ_{rt}, $\epsilon_{\theta t}$.

From these runs two concentration factors are calculated for each parameter to be adjusted.

Geometry factors

$$K_{\sigma g} = \sigma_{rs}/\sigma_{rc}$$

$$K_{\epsilon g} = \epsilon_{\theta s}/\epsilon_{\theta c}$$

Thermal load factors

$$K_{\sigma t} = \sigma_{rt}/\sigma_{rc}$$

$$K_{\epsilon t} = \epsilon_{\theta t}/\epsilon_{\theta c}$$

These concentration factors are then used to obtain the adjusted stress and strain values due to thermal gradients

$$\sigma_{rtg} = K_{\sigma g} \; K_{\sigma t} \; \sigma_{rax}$$

$$\epsilon_{\theta tg} = K_{\epsilon g} \; K_{\epsilon t} \; \epsilon_{\theta ax}$$

The values obtained from the horizontal slump, vertical slump, and thermal gradient analyses were then combined to obtain the predicted delta values of σ_r, ϵ_θ, and τ at the selected times and gage locations. All stress/strain values were considered 0.0 prior to lift to the vertical position.

4. Material Properties

Material properties used for this analysis (see Table III) were the same as those used in the previous analysis (ref 1) except for the equivalent viscoelastic propellant modulus. Also the Thiokol value for thermal coefficient of linear expansion (α)

was used. This value was chosen because it resulted in better correlation with test data in the previous analysis.

A procedure has been developed to reduce the required viscoelastic analysis to an equivalent elastic analysis. This is accomplished by the use of Programs S3069 and S3053. Input geometry to both programs consists of a cylinder with a 15.2 in. inner radius, a 32.7 in. outer radius, and a 0.144 in. case thickness. A viscoelastic analysis was run on Program S3069. Input to this program consists of relaxation modulus (E_{rel}) versus temperature reduced time (see Figure 6) temperature shift factor (A_t) versus temperature (see Figure 7) and time-temperature history of the motor. Output from this program is σ_r at the case/propellant interface as a function of time. An elastic analysis was then run on Program S3053 for thermal loads experienced during the test and various values of modulus. Output from these runs gives σ_r as a function of modulus. The output values from these two programs are then combined to obtain a modulus (equivalent elastic modulus) which will give the same interface stress in the elastic cylinder as is obtained from the viscoelastic cylinder analysis. Due to the complex thermal loading during the test, an effort was made to obtain an average value of E during the test cycle. This value is 160 psi and was used for all calculations during the test.

B. DYNAMIC ANALYSIS

Vibration loads were induced in the OOAMA/RPL stress motor by traversing a spaced board course with a GFE transporter pulled by a tractor. The load was varied by making a number of runs at different speeds.

The motor case had three triaxial accelerometers (see Figure 3): one at each end of the motor and the third located 50 in. aft of the head end (plane 50). A vertical accelerometer was mounted on the propellant at plane 50 (V4) 15 deg off the motor vertical axis. This accelerometer was used to determine the loads used for the analysis.

The previous analysis (ref 1) showed that predicted stress and strain values are linear functions of modulus (E) and acceleration loads (g). The relationships derived from these data are:

$$\sigma_{r2} = \sigma_{r1} \; (g2/g1)$$

$$\tau_2 = \tau_1 \; (g2/g1)$$

$$\epsilon_{\theta 2} = \epsilon_{\theta 1} \; (g2/g1) \; (E1/E2)$$

Where the subscript 1 refers to the reference parameters and the subscript 2 refers to the new parameters.

These equations in conjunction with the modulus shown in Table II were used to obtain the results also shown in Table II. The data obtained from ref 1 was:

$$\sigma_r = 1.56 \text{ psi}$$

$$\tau = 0.66 \text{ psi}$$

$$\epsilon_\theta = 0.07 \text{ percent}$$

$$g = 0.8 \text{ g}$$

$$E = 1{,}860 \text{ psi}$$

Dynamic modulus (E') was obtained from Figure 4 where E' equals 3G'. The curve of G' versus frequency (Figure 8) based on a JANNAF modulus of 800 psi was used whereas the previous analysis used the G' curve based on a JANNAF modulus of 500 psi (page 19, ref 1). This should give a more realistic value. Other material properties used in this analysis were the same as the previous analysis and are shown in Table III.

III. ANALYSIS RESULTS

A. TIP-OVER ANALYSIS

The results of this analysis are summarized in Table I. Values are reported for the applicable gages and for different loading conditions which occurred during

the test. The stresses and strains shown are predicted delta values from the time just prior to lifting the motor to the vertical position (5 Nov 1971 at 1745 hours). The final values shown are for the time (8 Nov 1971 at 1415 hours) just after the motor was lowered to the initial horizontal position. It should be noted that the final values did not return to a 0 delta value due to thermal changes that occurred in the motor during the test.

B. DYNAMIC ANALYSIS

This analysis was performed for selected times during each run over the board course (two times from Runs 1 and 5 and 1 time for Runs 2 and 3). These results are summarized in Table II and reflect only the stress and strain components due to vertical acceleration loading. Measured case longitudinal and tangential strains are shown in Table IV.

IV. CONCLUSIONS

The analytical prediction of stresses and strains to be measured in the OOAMA/RPL motor program have been presented. Although the analysis was not very refined, the predictions represent a reasonable best estimate of the stresses and strains to be measured.

The significance of all the OOAMA/RPL stress motor programs is that they will provide grain stress analysts with information previously unattainable. In the past, the grain analysts could not verify the accuracy of modulus dependent predictions because no means of verifying these predictions existed. The advent of usable stress/strain gages, however, now makes such means possible. Future investigations of instrumented motors will significantly extend the grain analysts' knowledge of grain structural behavior. The program presented in this report represents a major step towards this achievement.

V. REFERENCES

1. Thiokol Chemical Corporation: Final Report, Grain Stress Analysis Study, OOAMA/RPL Stress Motor S/N 0012257, TWR-4728, Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah. August 1971.

2. Dickson, E. C. and Lee, D. H.: IBM 360 Computer Program for Plane Strain Analysis, Program No. S3016, Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah. February 1970.

3. Dickson, E. C. and Lee, D. H.: IBM 360 Computer Program for Axisymmetric Stress Analysis, Program No. S3036, Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah. December 1969.

4. Schapery, R. A., Vogt, J. P., and Clemmek, L. E.: Studies Related to the Thermoviscoelastic Stress Analysis of Highly Loaded Solid Propellant, Purdue University AS and ES 66-6. February 1967.

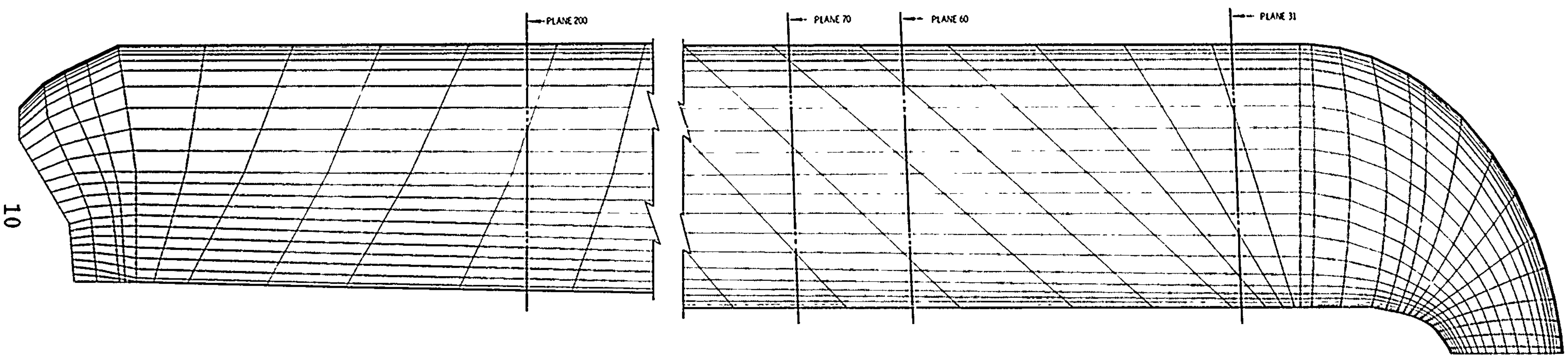

Figure 1. Axisymmetric Equivalent Port Area Stress Analysis Grid

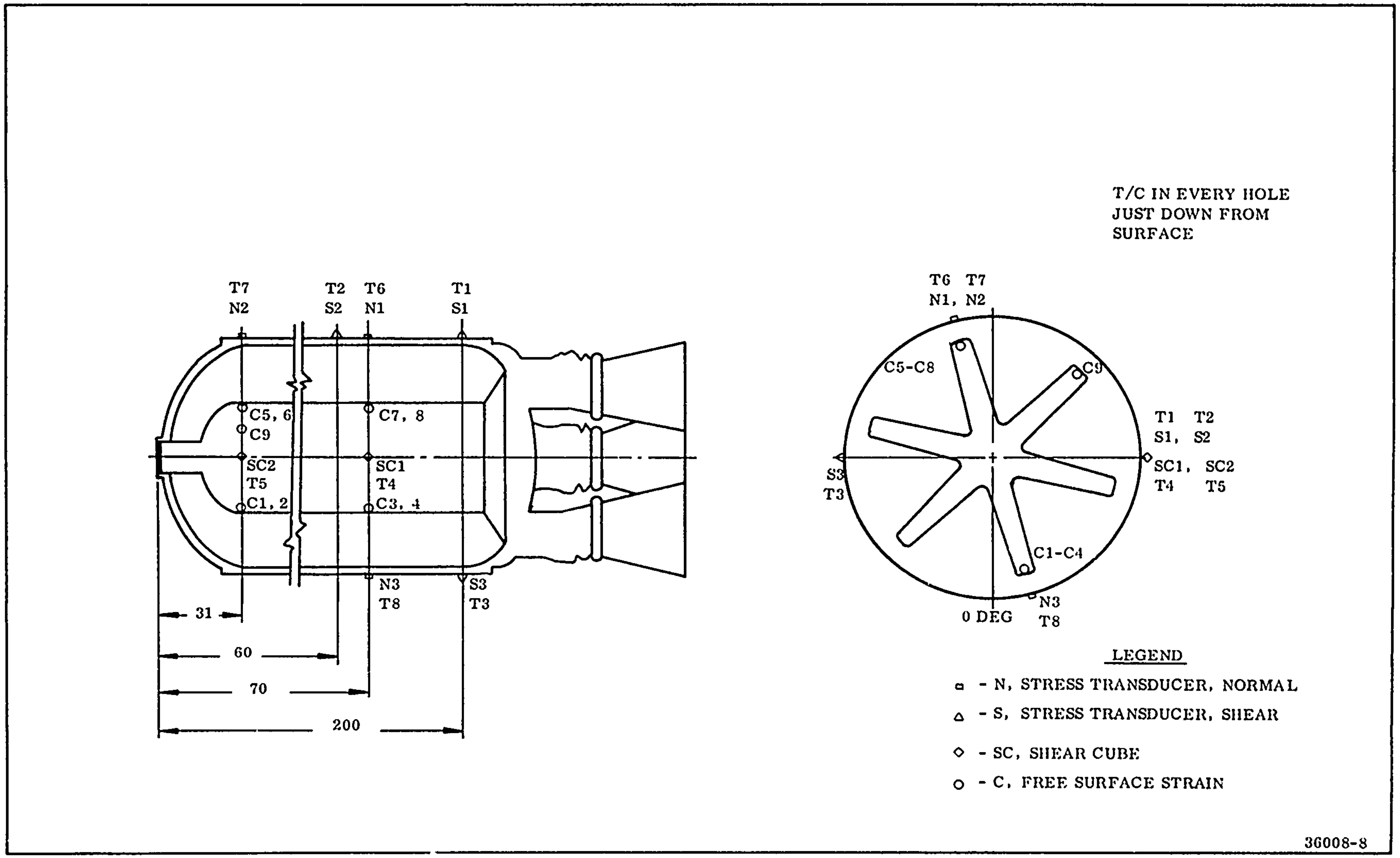

Figure 2. Propellant Stress, Strain and Temperature Instrumentation Location

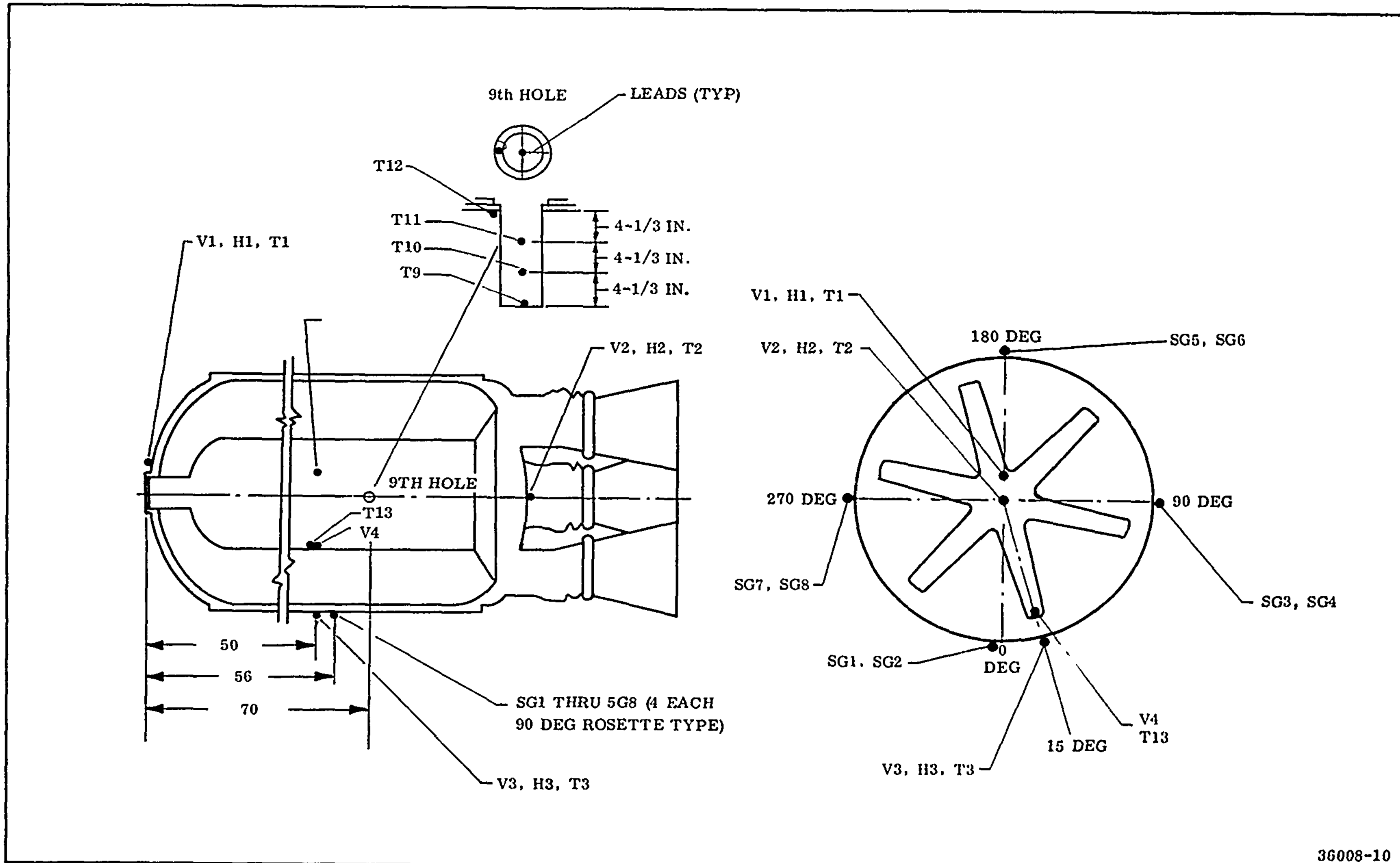

Figure 3. Case Strain, Acceleration, and 9th Hole Instrumentation Location

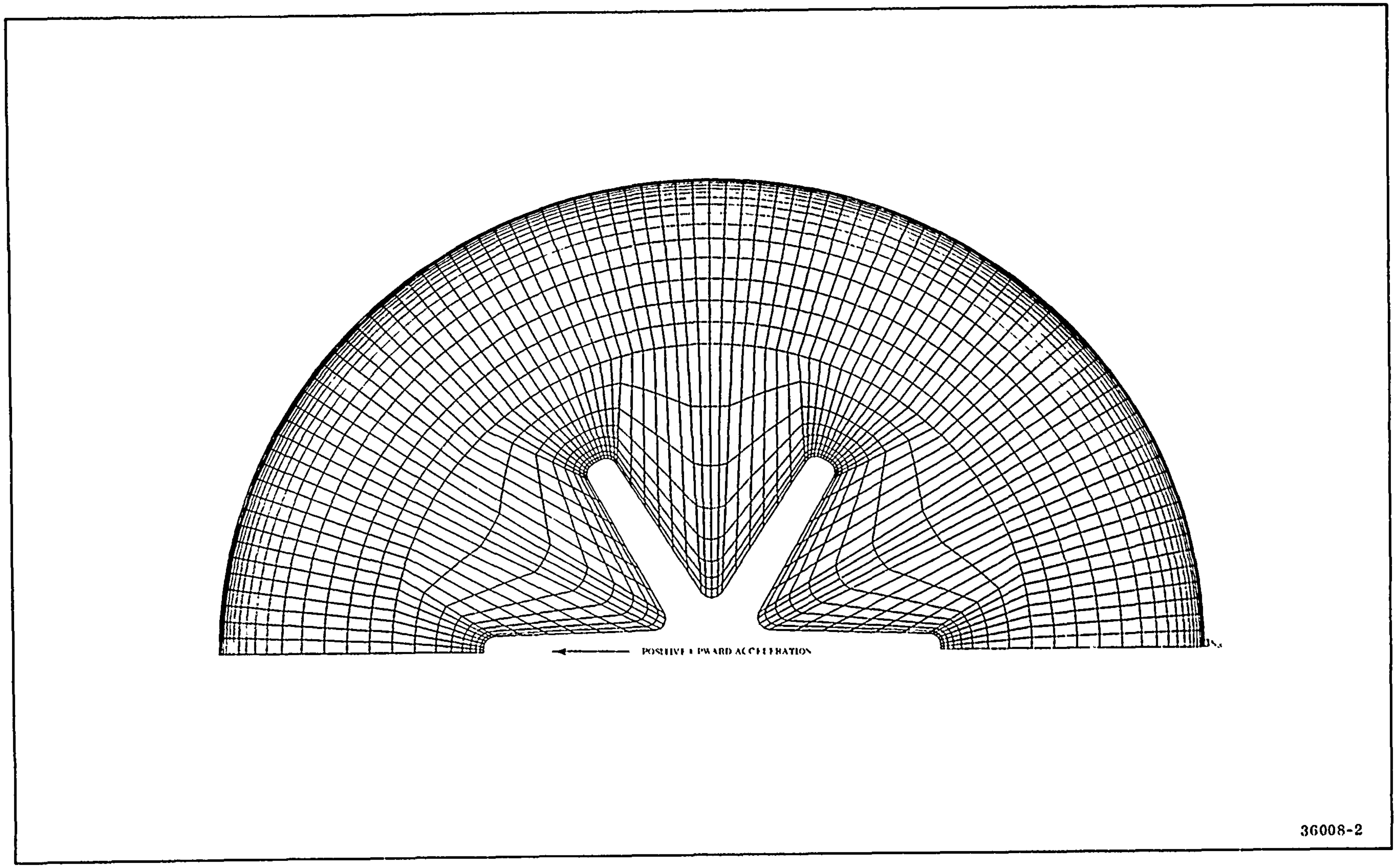

Figure 4. Dynamic and Horizontal Slump, Stress Analysis Grid

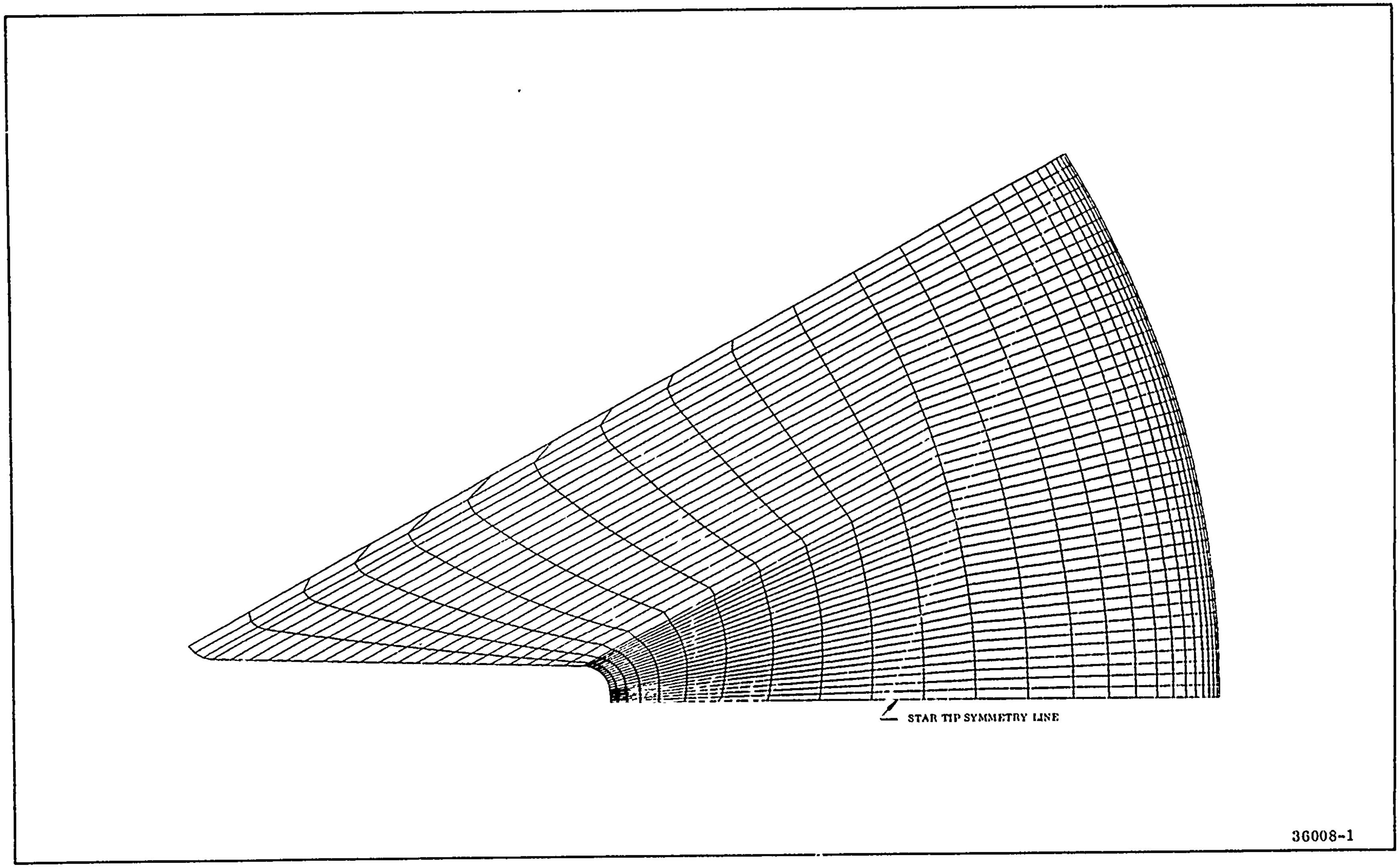

Figure 5. Thermal Stress Analysis Grid

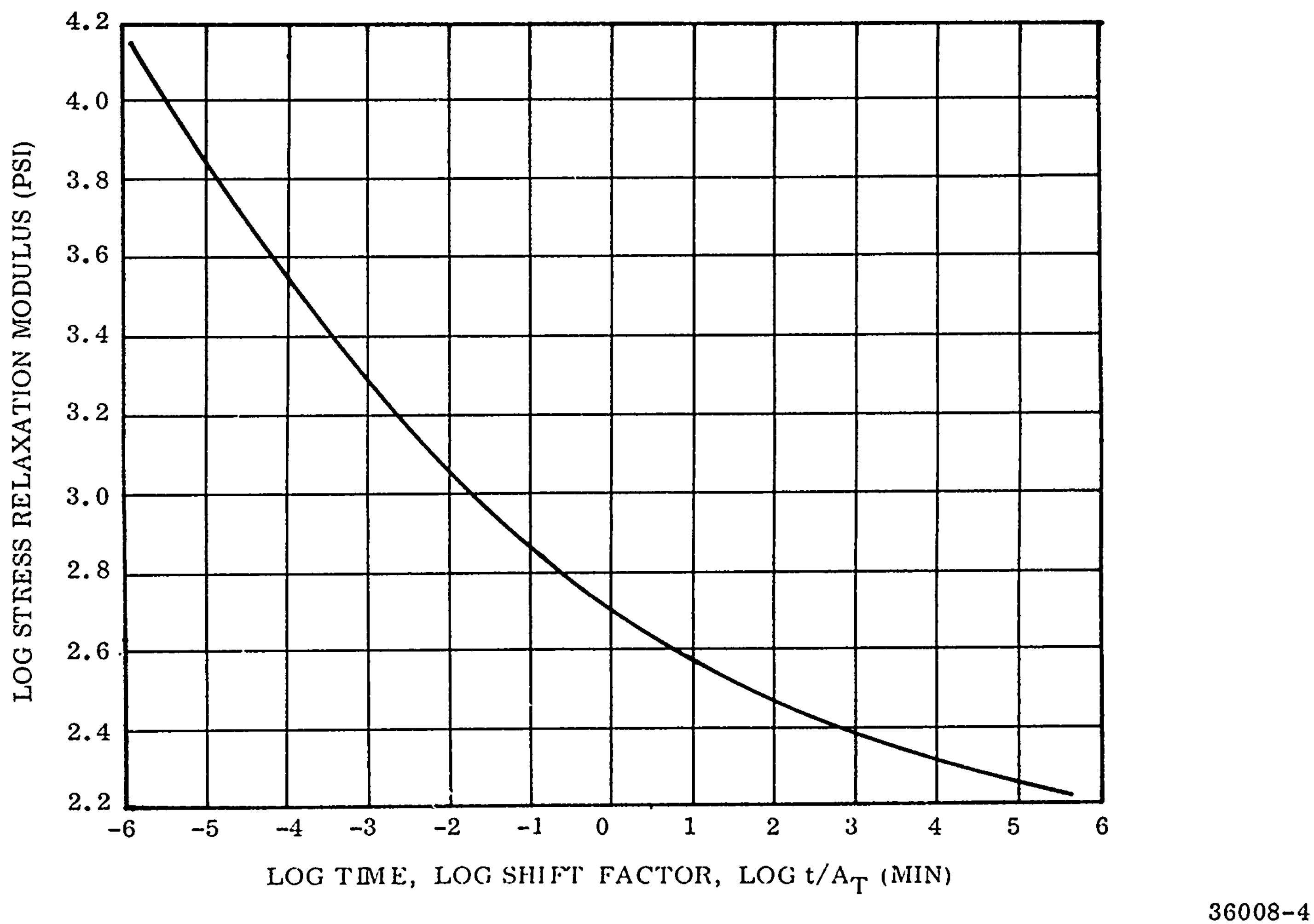

Figure 6. Stress Relaxation Modulus vs Temperature Reduced Time

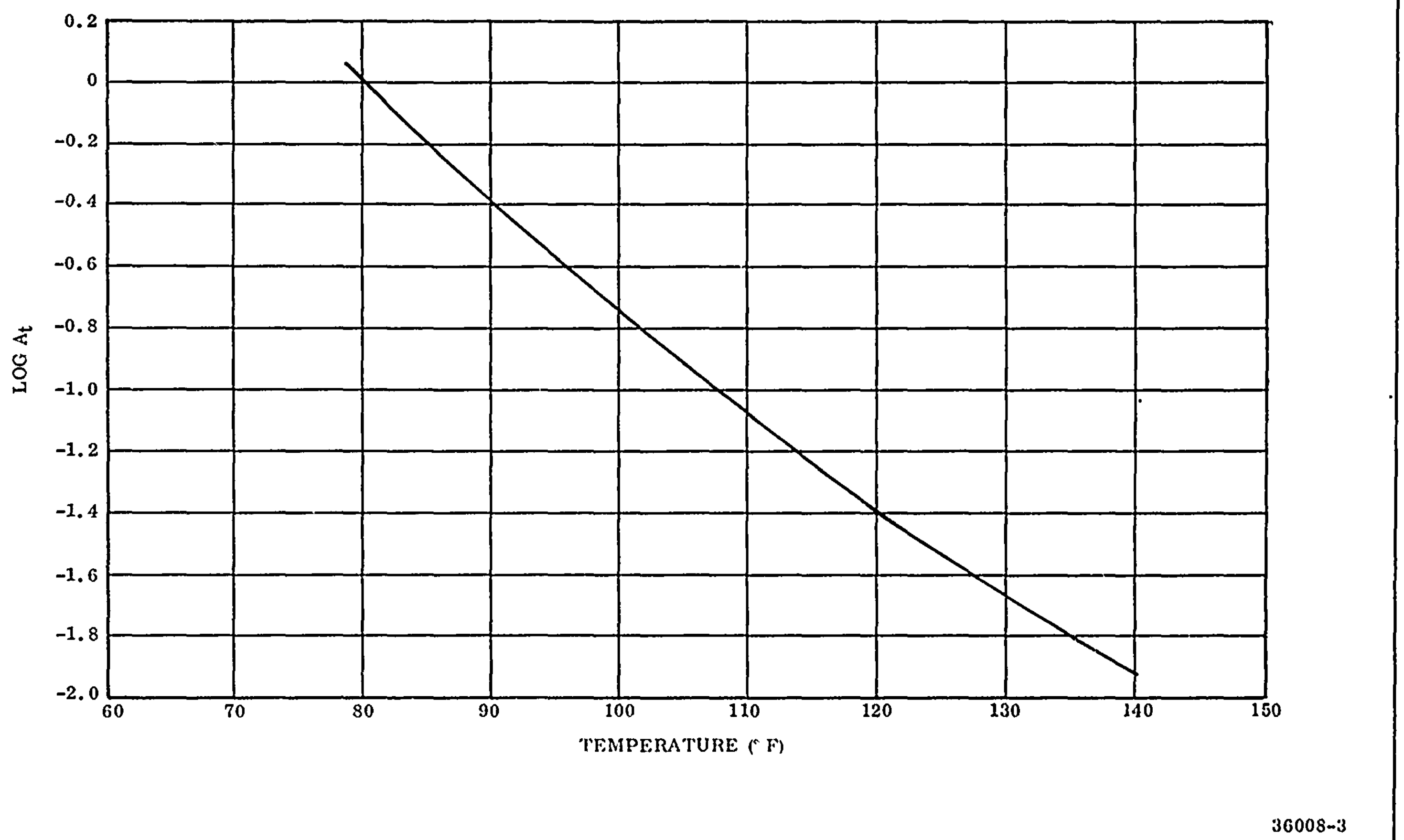

Figure 7. Temperature Shift Factor vs Temperature

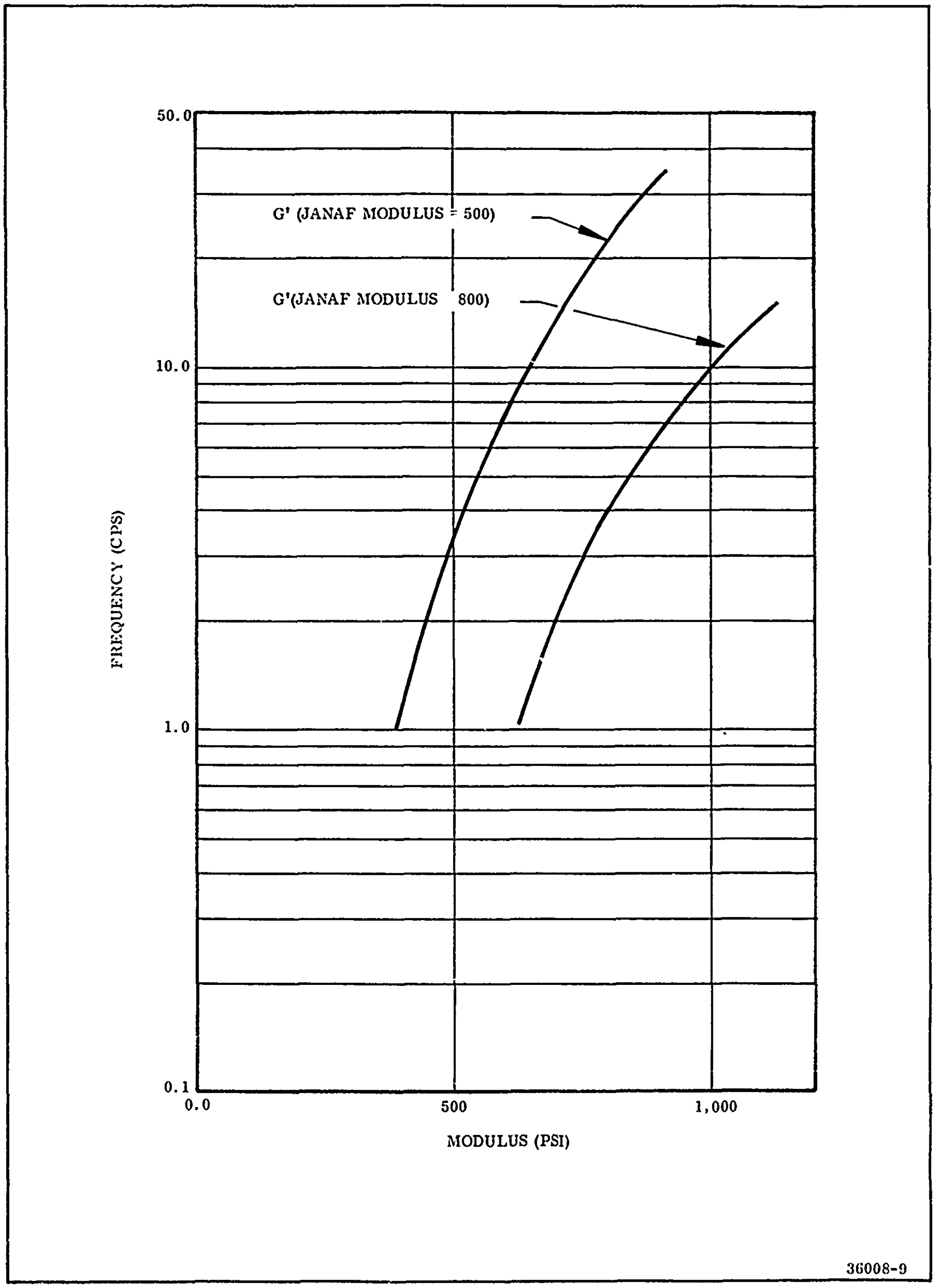

Figure 8. Dynamic Shear Modulus vs Frequency

TABLE I

TIP-OVER TEST ANALYTICAL STRESS ANALYSIS RESULTS

Position	Gage:	Normal Stress (psi)			Shear Stress (psi)					Star Tip Strain (percent)			
		N1	N2	N3	SC1	SC2	S1	S2	S3	C1-C2	C3-C4	C5-C6	C7-C8
Horizontal (11/5, 1745)*		0	0	0	0	0	0	0	0	0	0	0	0
Vertical (11/5, 1900)		-1.18	-0.35	2.59	0.69	0.34	0.87	0.65	0.87	2.71	1.97	0.44	-0.30
Vertical (11/6, 0400)		-1.09	-0.26	2.68	0.69	0.34	0.87	0.65	0.87	2.27	1.53	0.0	-0.74
Vertical (11/7, 0800)		-1.24	-0.41	2.53	0.69	0.34	0.87	0.65	0.87	1.20	0.49	-1.07	-1.78
Vertical (11/8, 1040)		-1.56	-0.73	2.21	0.69	0.34	0.87	0.65	0.87	1.07	0.36	-1.20	-1.91
Vertical (11/8, 1330)		-1.60	-0.77	2.17	0.69	0.34	0.87	0.65	0.87	1.20	0.49	-1.07	-1.78
Horizontal (11/8, 1400)**		-0.40	-0.40	-0.40	0	0	0	0	0	-1.23	-1.20	-1.23	-1.20
Horizontal (11/8, 1415)**		-0.40	-0.40	-0.40	0	0	0	0	0	-1.23	-1.20	-1.23	-1.20

*Equilibrium position.
**Values of normal stress and star tip strain result from thermal effects only.

TABLE II

BOARD COURSE VERTICAL RESPONSE AND STRESS ANALYSIS RESULTS

Run No.	Time (sec)	Acceleration* V4 (g's)	Modulus (psi)	Frequency (cps)	Normal Stress (psi)	Bore Strain (percent)	Shear (psi)
1	12.5	0.31	2,160	2.4	0.605	0.023	0.026
1	35.5	0.98	2,220	2.8	1.91	0.071	0.081
2	33.5	0.48	2,160	2.4	0.94	0.036	0.040
3	35.5	1.11	2,220	2.8	2.16	0.081	0.083
5	39.0	0.62	2,205	2.7	1.21	0.045	0.051
5	47.0	0.75	2,220	2.8	1.46	0.054	0.062

*Single amplitude acceleration, 1/2 (peak-to-peak)

TABLE III

MATERIAL PROPERTIES

	Case	Liner	Propellant
Tip-Over Analysis			
Poisson's Ratio	0.3	0.499	0.499
Modulus (psi)	30.0×10^{6}	130	160
TCLE (α) (in./in./°F)	7.076×10^{-6}	1.5×10^{-4}	54.0×10^{-6}
Dynamic Analysis			
Poisson's Ratio	0.3	0.499	0.499
Modulus	30.0×10^{6}	480	(See Table II)

TABLE IV

BOARD COURSE LONGITUDINAL AND TANGENTIAL CASE STRAIN

Run No.	Time (sec)	Acceleration (g's)	Case Strain (micro in./in.) SG1*	SG2**	SG3*	SG4**	SG5*	SG6**	SG7*	SG8**
1	12.5	0.31	50	10	45	0	45	13	59	25
1	35.5	0.98	95	10	71	0	85	11	97	37
2	33.5	0.48	53	13	45	0	54	13	67	27
3	35.5	1.11	88	13	62	0	88	13	94	36
5	39.0	0.62	67	11	85	0	58	10	80	32
5	47.0	0.75	56	11	26	0	56	15	40	13

*Longitudinal
**Tangential

See Figure 3 for gage locations.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Thiokol Chemical Corporation/Wasatch Div Brigham City, Utah	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Special Report, Grain Stress Analysis Study - Phases II and III (OOAMA/RPL Stress Motor SN 0012257)

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Special Report 1 Nov 1971 thru 29 Feb 1972

5. AUTHOR(S) *(First name, middle initial, last name)*

6. REPORT DATE	7a. TOTAL NO OF PAGES	7b. NO OF REFS
February 1972	25	4

8a. CONTRACT OR GRANT NO F04611-72-C-0015 b. PROJECT NO c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TWR-5605 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Distribution limited to U.S. Gov't agencies only: (Information covering test and evaluation of military hardware); (February 1972). Other requests for this document must be referred to AFRPL (STINFO/DOZ), Edwards, CA 93523.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Rocket Propulsion Lab Air Force Systems Command Edwards AFB, California

13. ABSTRACT

This report presents a theoretical stress analysis of OOAMA/RPL motor S/N 0012257. The analysis involved motor tip-over from horizontal to vertical position and rerun of the board course reported previously in Thiokol document TWR-4728. The results reported represent a major step in the use of instrumented motors to verify the accuracy of modulus dependent predictions of rocket motor grain structural behavior.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

UNCLASSIFIED

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

UNCLASSIFIED

Security Classification